Problem and Research Objectives:

Low Impact Development (LID) techniques for site design are increasingly being utilized to mitigate the negative impacts associated with stormwater runoff, and green roofs are one such application. The ability of green roofs to reduce the total and peak volumes of stormwater runoff has been fairly well documented, but performance varies in different climate zones, and there is limited information available regarding green roof effectiveness in New England, a region whose weather patterns are notoriously variable from season to season and often even day-to-day. Additionally, there are questions regarding the impact that green roofs have on water quality. While there seems to be a general consensus that green roofs will leach phosphorus, and sometimes other contaminants, into stormwater runoff within the first few years after installation, it is assumed that this phenomenon will not continue after the green roof vegetation has been established. However, it is still unclear whether or not this assumption is valid, and very few research projects have attempted to provide the necessary insight into the hydrologic and chemical processes that are contributing to this question.

Accordingly, the goals of this research were to provide insight into the hydrologic and geochemical processes that contribute to green roof performance. The specific objectives included the following:

- Determine the effectiveness of a green roof in attenuating stormwater flow
- Document a green roof's impact on water quality, specifically regarding phosphorus
- Identify the key components of the processes that are likely leading to the highest variability in observed water quality parameters – hence, the highest potential that a change in design could lead to significant improvements

In addition to providing insight into green roof performance, these objectives are intended to provide a foundation for future research efforts to explore the behavior of phosphorus in soil solutions and its implications for stormwater treatment.

Methodology:

The methodology for achieving the project objectives combined field monitoring and laboratory testing and analyses to characterize the quality of runoff associated with the Nitsch/Magliozzi Green Roof, an extensive green roof located on top of a new residence hall at WPI. This roof, which was donated to enhance the sustainability of the building and foster continued research and education, provided the context for this project. The research tasks included field monitoring of the roof drainage, laboratory testing of green roof panels under simulated rainfall conditions, bench-scale testing of phosphorus desorption from the growing medium, and laboratory analyses of water quality, soil characteristics, and plant phosphorus content. The methodology provided a basis for gaining a better understanding of the relationship between rainfall and runoff volumes, phosphorus sorption/desorption in the growing medium, and plant uptake processes.

The field monitoring program focused on the seasonal variations of water quality throughout a complete growing season. Two flow meters and sampling ports have been installed within the storm drain system of the residence hall: one to measure drainage from the green roof; and the other to measure drainage from the "non-green" portion of the roof. Using these sampling ports, a total of 25 grab samples from each roof were collected and analyzed between June 2009 and April 2010.

The laboratory testing and analysis program was developed to characterize both the stormwater retention performance and water quality characteristics of the green roof. For this program, two (2) of the green roof panels were brought into a greenhouse maintained at WPI by WPI's Biology Department. A stand was constructed which allowed for the application of simulated rainfall and collection and measurement of runoff for each panel. For water quality monitoring, runoff from each panel was detoured through a flow-through device attached to a water quality monitoring sonde (Hach MS5 Hydrolab unit), and grab samples were collected at key points during the simulated storms. The Hach MS5 Hydrolab units, one of which was acquired using support from this grant, were important components of this system. Soil and plant samples were also collected, and additional bench-scale tests were completed to characterize the nature of the phosphorus desorption from the media. All samples of water, plant, and soil were analyzed in the water quality laboratory in WPI's Department of Civil and Environmental Engineering.

Principal Findings and Significance:

In regards to storm-water flow attenuation, results from the greenhouse experiments showed that green roof performance was more effective for smaller storms, and was influenced by the soil properties (including field capacity and moisture content). Overall, these results are consistent with the published literature. For example, the reduced retention capacity observed during higher flow conditions is a common trend that has been reported for extensive green roof performance. At high rainfall intensities, the field capacity of the green roof panels is quickly exceeded, and the thin layer of the extensive green roof design does not provide much storage capacity. However, while the growing medium did not provide much storage during the heavier simulated rain event, the green roof vegetation's ability to rapidly uptake water when it becomes available did provide a stormwater retention benefit. The improved performance during the lower flow conditions was found to be more heavily influenced by the soil than by the plants. The highest retention rates in the simulated rain events were observed when the antecedent moisture content was low (9-11%). For a light rain event, the moisture content of the soil at the beginning of the rainfall was the highest of all tests (26%), and the green roof panels retained only 38% of the influent volume, despite the fact this simulated storm used the smallest volume of water of all simulated events. Clearly the growing medium's field capacity is a critical design factor that is indicative of green roof performance.

In regards to water quality, phosphorus concentrations observed in runoff during green house tests, were similar in magnitude to the concentrations in samples collected from the green and white roofs, which were relatively high. These high concentrations were found to be primarily influenced by phosphorus in the growing medium, which quickly desorbs in response to flushing due to storm events. For all greenhouse tests, the phosphorus concentrations (and other constituents as well) showed up in the "first flush" runoff samples and continued to increase throughout the duration of the storm and after the simulated rainfall had stopped. This trend was consistently observed in all storms, regardless of their size or intensity. These results indicate that the desorption process quickly starts removing the phosphorus from the growing medium. However, the soil is not rapidly depleted of its phosphorus content. Also, the green roof panel whose soil was higher in phosphorus concentration (Stand B) also produced runoff with higher phosphorus concentrations than the other panel tested in the greenhouse (Stand A). Meanwhile, the growth of green roof plant material and its associated nutrient uptake processes did not appear to reduce the amount of phosphorus that ended up in the runoff. These results confirm that the growing medium is the source of phosphorus in runoff. However, while a bench-scale laboratory experiment indicated that phosphorus levels in runoff may decrease over time, the rate of desorption is not constant and cannot be easily predicted. Additional investigations will be needed in order to predict the long-term impact of a green roof on phosphorus loading.

With consideration to the design of green roofs, a number of key processes/factors were defined. First, this research showed that soil storage and soil moisture content are particularly important considerations with respect to green roof performance. Soil storage is heavily influenced by antecedent moisture content, and soil moisture content is a function of both weather, which cannot be controlled, and plant variety, which generally can be controlled. These results should help future designers determine whether the weather patterns in a particular location where a green is being considered will be hindrance to the effectiveness of a green roof. Areas experiencing significant amounts of rainfall that may keep the soil at field capacity would not be a good choice. However, selection of plant varieties that quickly uptake water, such as sedum and delosperma, will provide the ability to regenerate the holding capacity of the growing medium and will improve the performance of green roofs. Also, efforts should be taken to engineer new soil media that will maximize the field capacity of green roof designs. Second, the research showed that the leaching of phosphorus from the growing medium must be taken into consideration when designing a green roof. Previous studies have made assumptions that the leaching of phosphorus will decrease over time and many have predicted that the phenomenon will only occur for a few years after installation. However, the results of this study indicate that this assumption may not be valid. The long-term phosphorus loading resulting from a green roof may continue longer than previously assumed. Until additional investigations are conducted to develop a prediction model, the impacts of a green roof must be given careful consideration if being installed where phosphorus levels in stormwater are a concern. Further, it is recommended that phosphorus use be minimized in the growing medium. The typical green roof plant varieties, such as those studied here, do not appear to uptake very much of this nutrient, even in their first few establishment years.

In general, these results provide a basis for developing improved predictions of storm-water retention performance, gaining deeper insight into the transformations of phosphorus in the green roof panels, and developing a process by which continued, in-depth study could be performed under controlled laboratory and field conditions.